TOWARD IMPROVING THE OPTACON

by

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Abstract

The Optacon--a successful optical-to-tactile-conversion reading aid for the blind--has historically had a display window of slightly less than one letterspace. What would be the effect of widening that display window?

In finding an answer to this question, a model of the human reading system has been formulated, based upon the results of several reading experiments (both visual and tactile). The model indicates that there is a mental processing period with an average duration of 90-95 ms. It also indicates that new information is accepted only at the beginning of a processing period. However, a single "load" of information may utilize one, two, or more consecutive processing periods. In addition, the source of information (tactile, auditory, visual, etc.) may be different each time new information is accepted, which is simply an embodiment of the time-sharing principle.

Since these characteristics are general, the model is actually applicable to a wide range of mental tasks extending well beyond reading. As it applies to the reading task, however, this model closely predicts data from several reading experiments. It has given us a much better understanding of the interactions involved in reading. The model also shows ways for improving the Optacon so that better reading performance can be attained by the blind reader, and these improvements are being experimentally verified at this time.

Introduction

The Optacon--a successful optical-to-tactile-conversion, direct-translation reading aid for the blind--was originally conceived in the early 1960's by Dr. John Linvill at Stanford University. In concept, this device consists of an array of photosensors connected to an array of tactile simulators by some appropriate electronics. When an area of print is imaged upon the photosensor array, a corresponding tactile image is reproduced on the stimulator array. This tactile image, which is a direct facsimile of the area of print, is in turn sensed by the blind reader. Figure 1 shows an Optacon in use.

Constant-Rate Reading

While Dr. Linvill and his associates were studying the feasibility of producing a working Optacon, one question repeatedly arose: What is the best display window width, i.e., horizontal field-of-view, to use? In 1965, Bliss made an initial measurement of the effect of window width changes, and the results

FIGURE 1. SUBJECT USING A RECENT MODEL OF THE OPTACON. The camera is held in her right hand and manually scanned across the print while she detects the tactile images with the index finger on her left hand.

of his experiment are shown in Figure 2.(1) Bliss used a 12-row high array of tactile stimulators placed against a single finger tip. The stimulators were driven by a computer-generated, constant-rate, moving-belt display of English prose at 24 wpm. The window width was varied by changing the number of active display columns. He found that the reading rate, as measured in correct words-per-minute, increased as the window width increased from zero to a half of a letterspace (ℓs). (A letterspace is defined as the width of a letter plus the space between it and the next letter.) However, no additional increase was recorded when the window width was increased further. Since there was reason to believe that the subject's finger did not adequately contact the array over more than half a letterspace, it was

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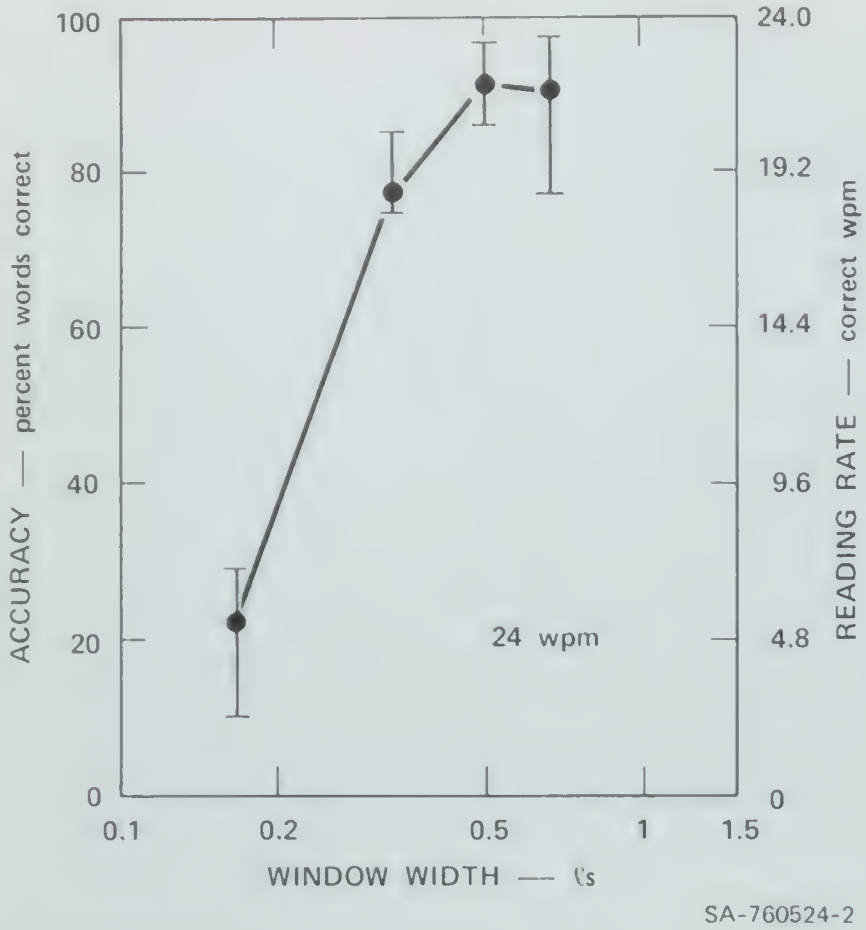

FIGURE 2. RESULTS OF A TACTILE READING EXPERIMENT BY BLISS (1). One subject after 21 hours of training—average of three trials.

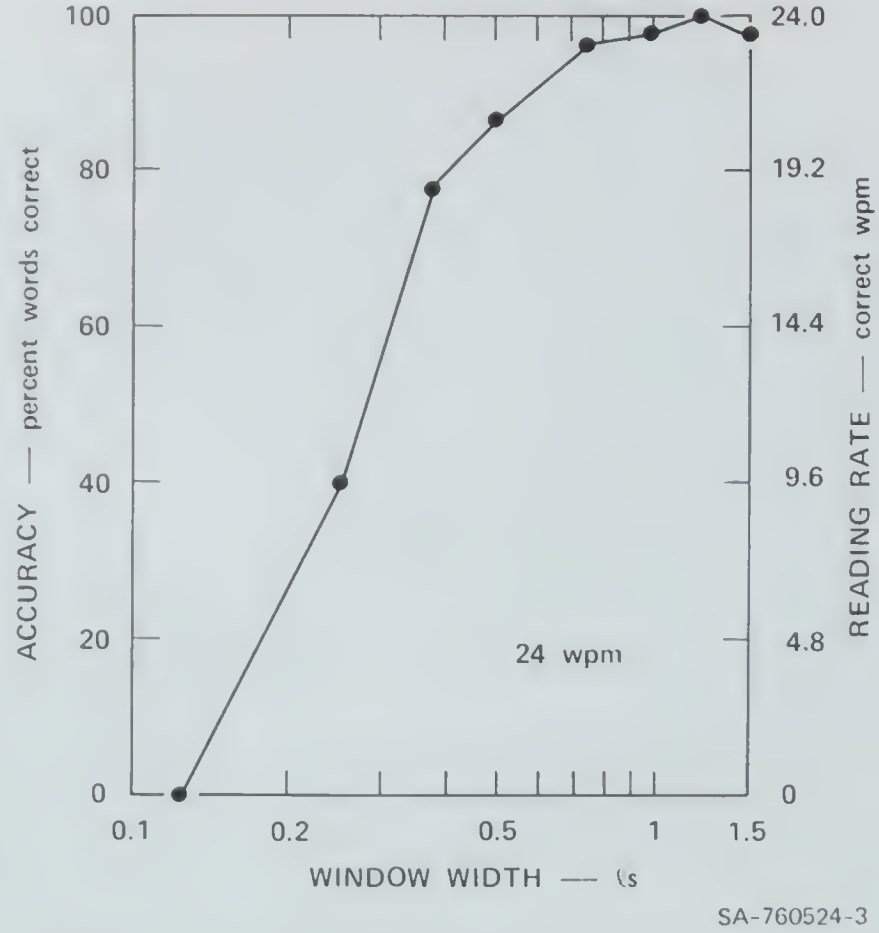

FIGURE 3. RESULTS OF A VISUAL CONSTANT-RATE EXPERIMENT. Average results for four subjects after 12 hours of training.

assumed that the reading rate would continue to increase for wider window widths if the additional information could be adequately displayed to the subject.

In 1968, I ran a similar experiment in which the reading was done visually using a light box display (2). The display parameters were virtually identical to those that Bliss used. Figure 3 shows the results of that experiment. For window widths up to 0.5 ℓs the results are practically identical to those reported by Bliss. Beyond 0.5 ℓs the continuing increase that Bliss expected is also evident. It was somewhat surprising to find that the visual and tactile reading results were nearly identical--at least for small window widths. This was one of the earliest indications that both visual and tactile information is handled by the same mental processing mechanism.

These measurements at 21 wpm have a limitation however: the curves saturate at 100% accuracy for window widths of 1.0 ℓs or more. In order to measure the effect of wider windows, the display rate must be increased. Therefore I ran the same experiment again, but at a 60 wpm display rate. All other parameters remained the same. Figure 4 shows the results of this higher rate experiment. The reading speed continued to increase to the 1.5 ℓs limit of our display. Thus the data indicates that higher reading speeds and wider window widths go hand in hand.

If you have been looking closely, you have noticed that the shapes of the two visual curves are nearly identical. The major difference is that the higher display rate curve is displaced to the right of the lower display rate curve. However, if the visual results are plotted as word accuracy versus display time, where display time is defined as the amount of time any part of a letter is being displayed while moving from the right edge to the left edge of the window, then a single performance curve results. For any combination of window width and display rate there is a unique display time. The display time, t_d, is given by

$$t_d = \frac{W}{S_d} \qquad (1)$$

where W is the window width and S_d is the display rate. Figure 5 shows the performance curve that results from this manipulation. It indicates that for display times of 50 ms or less, word reading is nearly impossible. As the display time increases the accuracy increases reaching 50% at 95 ms display time. Likewise 95% accuracy, which closely corresponds to 100% comprehension, is achieved with a 150 ms display time. Thus, for constant-rate displays, these data indicate that the effect of changes in window width follow Equation (1) with the display time, t_d, being a constant having a value of 150 ms for high comprehension reading. Equation (1) is a linear relationship where doubling the window width

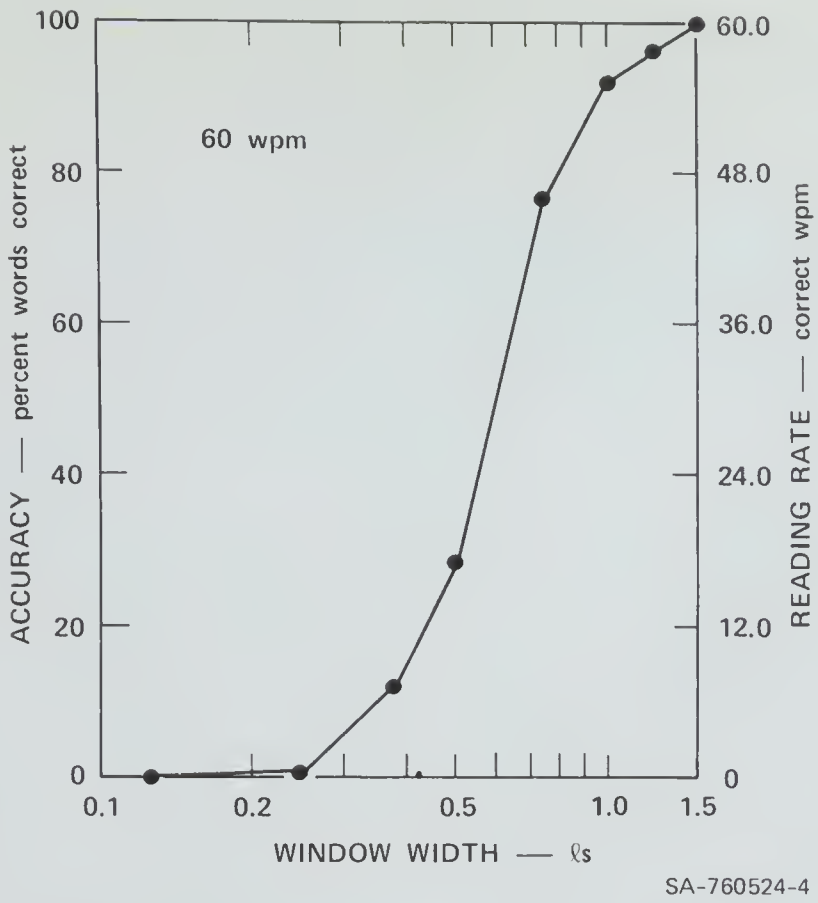

FIGURE 4. RESULTS OF A HIGHER RATE VISUAL EXPERIMENT. Average results for four subjects after 12 hours of training.

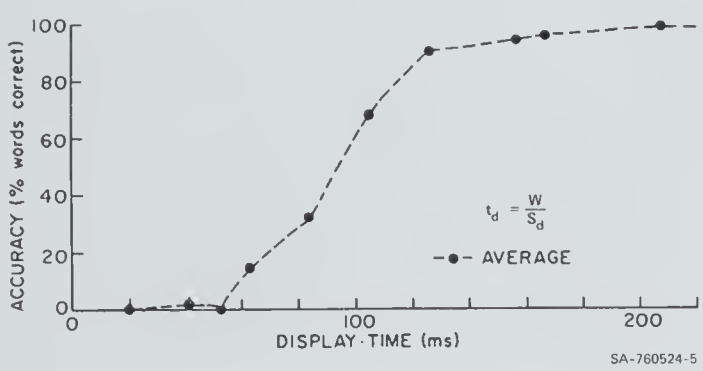

FIGURE 5. PERFORMANCE CURVE THAT RESULTS FROM THE COMBINED 24 wpm AND 60 wpm VISUAL DATA

doubles the readable display speed. Although these experiments involved window widths of less than 1.5 ℓs, the results of experiments performed by Poulton (3) and White (4) indicate that Equation (1) holds out to 5 or more letterspaces.

Free-Rate Reading

Since a constant-rate display does not involve any action on the part of the reader, it is not representative of the typical reading situation. I call a reading situation where the reader has complete control of the reading process the free-rate reading situation. Free-rate reading is different from constant-rate reading in two important ways. First, the reader has control of the rate at which the textual information is scanned, and therefore he can tailor his instantaneous scanning rate to his own instantaneous mental information processing speed. Secondly, free-rate reading entails the control of some mechanical scanning mechanism, such as the eye (for visual reading) or the arm and hand (for Optacon reading), and some mental processing time must be devoted to this tracking task. Therefore free-rate reading could be faster or slower than constant-rate reading depending on whether the increase due to being able to match the scanning rate to the processing requirements offsets the decrease due to the added tracking task.

In order to determine some of the effects of reader control, an experiment was run with an Optacon and blind subject (5). In this experiment the scanning time was monitored for each word that was read. Scanning times were determined to the nearest millisecond by a computerized measurement system operating in conjunction with a Grafacon tablet. The Grafacon tablet (like a Rand tablet) determined the X - Y position of the Optacon camera and told the computer where the subject was reading in the text. Thus the computer was able to calculate the scanning time for each word of the text whenever a word boundary was crossed. The textual material had a total of almost 1500 words.

After having collected the data, the effects of word length and word rank were investigated, and it was found that the average scanning-time-per-letterspace was quite constant over wide ranges of these variables; the overall average scanning-time-per-letterspace being 141.1 ms. However, the scanning time histograms for each word length, as shown in Figure 6, show details which cannot be accounted for by the noise in the measurements. If these scanning rate variations are somehow connected with the subjective meaning in the text, then variations with word length or rank would not necessarily be noticed, and yet the scanning rate measurements would contain a lot of information about the mental processing involved in reading. It was decided to formulate a mental processing mechanism model which would, hopefully, provide a good fit to the measured scanning time data, and such a model has been found. This model, which can be described in mathematical terms, represents the probability that the information contained in each window width of distance along a line of text will be correctly identified. A detailed description and mathematical derivation of the model is given in Reference (6). I will not repeat that exercise here but will, instead, give some of the features of the model.

Mental Processing Model

The mental processing model is based upon several assumptions. First of all, it is assumed that there is a mental processing period during which the processing of information is accomplished. New

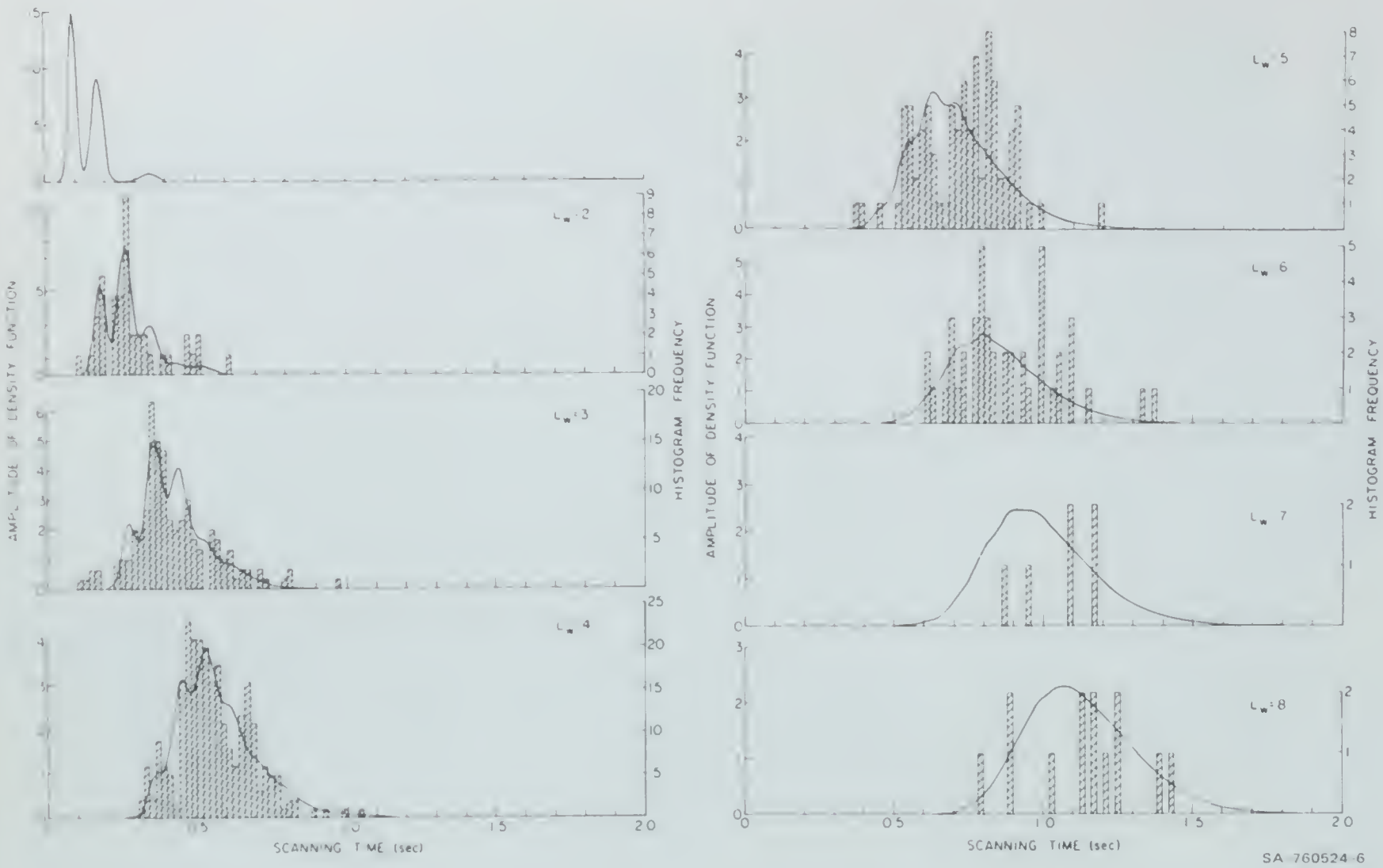

FIGURE 6. HISTOGRAMS OF THE SCANNING TIME DATA FROM A FREE-RATE TACTILE READING EXPERIMENT. Also shown are the smooth curves that result from the mental processing model described in (4).

information is accepted only at the beginning of a processing period. Furthermore, new information can be accepted from any source at the beginning of any processing period, or, to put it more simply, the processing mechanism is time-shared. It is further assumed that the duration of all processing periods is not precisely the same, but rather varies in a gaussian manner with mean and standard deviation. It is also assumed that a single load of information can be retained by the processing mechanism for any number of processing periods if necessary.

These features were incorporated in the mathematical model and a computer-based curve fitting exercise was performed using the model and the experimental data. Figure 7 shows the resulting single-window-width probability density function. Since the Optacon which was used for this experiment had a window-width of very nearly one letterspace, the probability density functions for words of any length can be produced by convolving the single-window-width probability density function with itself--once for each character in the word. The scanning time histograms are simply the measured versions of these

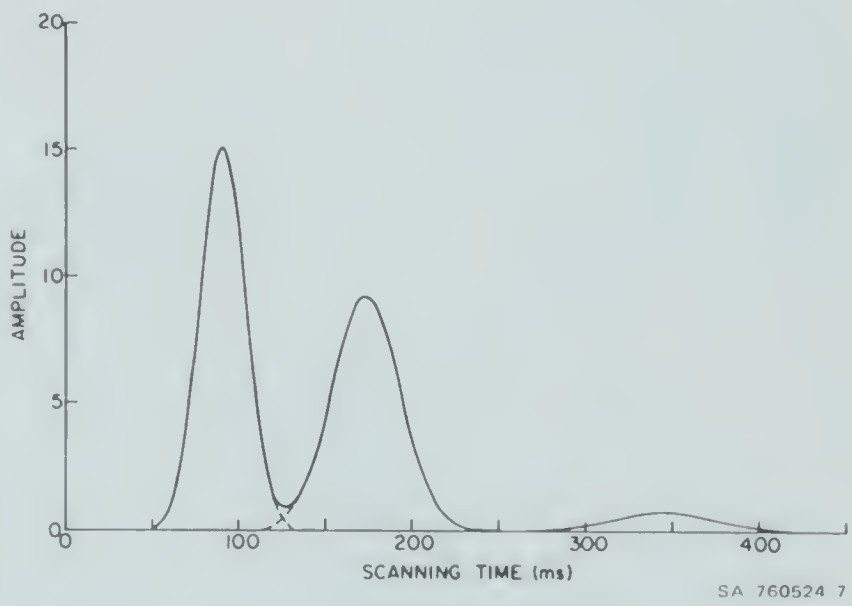

FIGURE 7. THE SINGLE-WINDOW-WIDTH PROBABILITY DENSITY FUNCTION GIVEN BY THE MENTAL PROCESSING MODEL.

density functions. Figure 6 compares the results from the model with the experimental data.

By fitting the model to the data, numerical values for some of the features of the model can now be identified in Figure 7. The peaks in the figure correspond to the processing periods. Each processing period has a duration of approximately 90 ms on the average with a standard deviation of 15 ms. In addition, slightly over half of the textual information requires only one processing period while the remainder is processed in two periods. (The small peak at 350 ms is thought to be an artifact due to the way in which the scanning time was measured.) Apparently only two processing periods at most are needed, and this came as a surprise. Another surprise was the 50 ms dead time before information appears to be processed. You may remember that the same result was found in the constant-rate visual measurements (Figure 5), but to also find it in the free-rate tactile measurements was beyond expectations. One more numerical result can be compared. The mean value of the single-window-width probability density function is 140.89 ms--very close to the 141.1 ms measured value.

The Effects of Tracking

This model describes the mental information processing mechanism involved in reading, but if we are to fully describe free-rate reading we also need a description of the additional task of tracking. In 1970, Franco Bertora, who was working on the Optacon project at Stanford University, ran an experiment which gave a measure of the effect of the tracking task (7). Bertora programmed a computer to produce a visual display which in many respects was similar to those used in the previously described constant-rate visual experiments. In addition he built a tracking device modeled after an Optacon camera. This device provided X-Y signals to the computer so that the subjects could control the displayed image. As the tracking probe was moved, the image moved in synchrony. Thus, the display was a visual analogy to an Optacon.

Bertora varied the window width, and measured the reading speeds of five well-trained sighted subjects. His results are shown in Figure 8 as black dots for each of the three window widths he measured. When he tried to fit his data with the constant-rate equation

$$S_d = \frac{W}{t_d} \qquad (2)$$

he found very poor agreement, however I suggested that he try an equation of the form

$$S_r = \frac{W}{t_p + W\tau_t} \qquad (3)$$

where

S_r = reading (scanning) speed (ℓs/sec)

W = window width (ℓs)

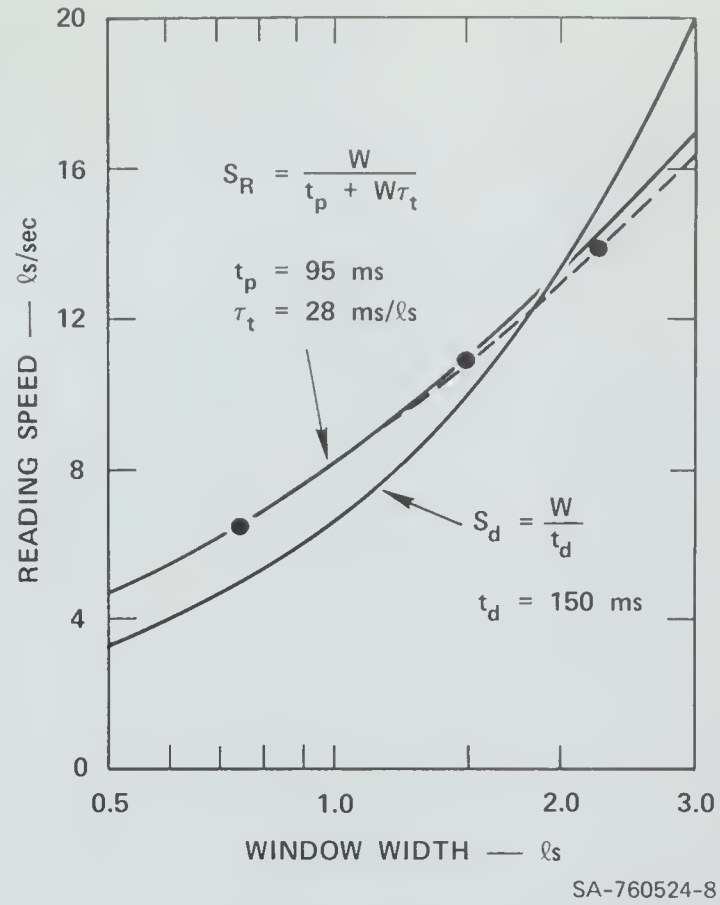

FIGURE 8. DATA MEASURED AND EQUATION DERIVED BY BERTORA (5) FOR A FREE-RATE VISUAL READING EXPERIMENT DESIGNED TO MEASURE THE EFFECT OF THE TRACKING TASK. Average for five subjects.

t_p = perception and processing time (sec)

τ_t = tracking constant (sec/ℓs).

This equation results from an assumption that, in free-rate reading, the time needed to process the information in each window width of distance along a line of text is made up of two parts: the textual information processing time and the tracking information processing time. Furthermore, it is assumed that the average tracking time for a line of text is only a function of the reader, the text material and the tracking system (eye, arm and hand, etc.). Thus, as the window width increases, the amount of time spent on tracking will also increase in proportion.

From his data, Bertora determined that the values

$$t_p = 95 \text{ ms}$$

$$\tau_t = 28 \text{ ms/ℓs}$$

would give a curve that fit his data (see Figure 8). However, I find that

$$t_p = 92 \text{ ms}$$

$$\tau_t = 31 \text{ ms/ℓs}$$

give an even better fit (dashed line in Figure 8).

By finding that it takes about 30 ms on the average to process the tracking information contained in each letterspace of distance along a line of text when the tracking is done manually, we have determined the effect that this tracking task has on free-rate reading. Since the processor is time-shared, the time spent processing the tracking information must reduce the available processing time for textual information. Thus for manual tracking and a 1.0 ℓs window width, one out of every four processing periods is devoted to the processing of tracking information; for a 3.0 ℓs window width the ratio is one out of every two periods.

It is expected that for other tracking systems, the tracking constant will have other values. For instance, for normal visual reading the eye is the tracking system. It can be moved quite rapidly and few muscles are involved in producing the motion. For this system the tracking constant may be as small as 10 ms.

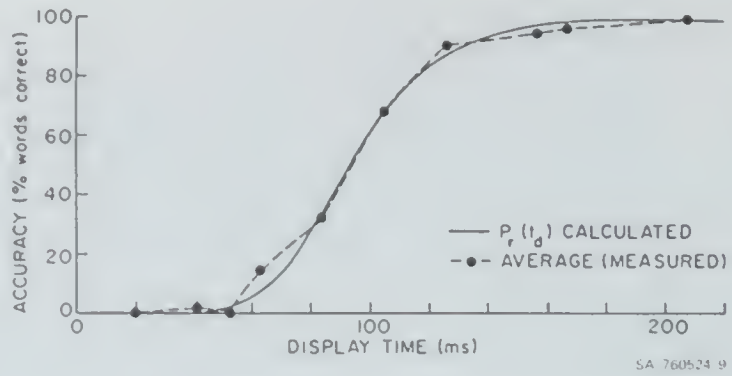

FIGURE 9. COMPARISON BETWEEN THE PERFORMANCE CURVE FROM FIGURE 5 AND THE PREDICTED PERFORMANCE CURVE DERIVED FROM THE RESULTS OF BERTORA AND THE MENTAL PROCESSING MODEL.

Using the Reading Model

We now have a good model of the free-rate reading process. One of the most important aspects of any model is its ability to predict performance, and this model does quite well in that department. By using the probability density functions for each word length (Figure 6), Equation (2), and Zipf's law (8)

$$P(n) = C/n, \quad C = 0.1 \quad ,$$

a predicted version of the performance curve measured in the constant-rate visual experiments (Figure 5) can be found. This predicted curve is shown in Figure 9 along with the measured data. As can be seen the agreement is quite good.

Since the model indicates that only the processing of information is important and not the spacing, it would predict that the effect of changes in interletter spacing would be negligible over a wide range of values. An experiment was run with a constant-rate tactile display in which the amount of space between the letters was varied. The subjects read connected English prose at two different display rates. Figure 10 shows the results of that experiment. The vertical bars at each data point indicate plus and minus one standard deviation; the theoretical curves were generated from the model. Again the agreement between the theoretical and the measured results is good.

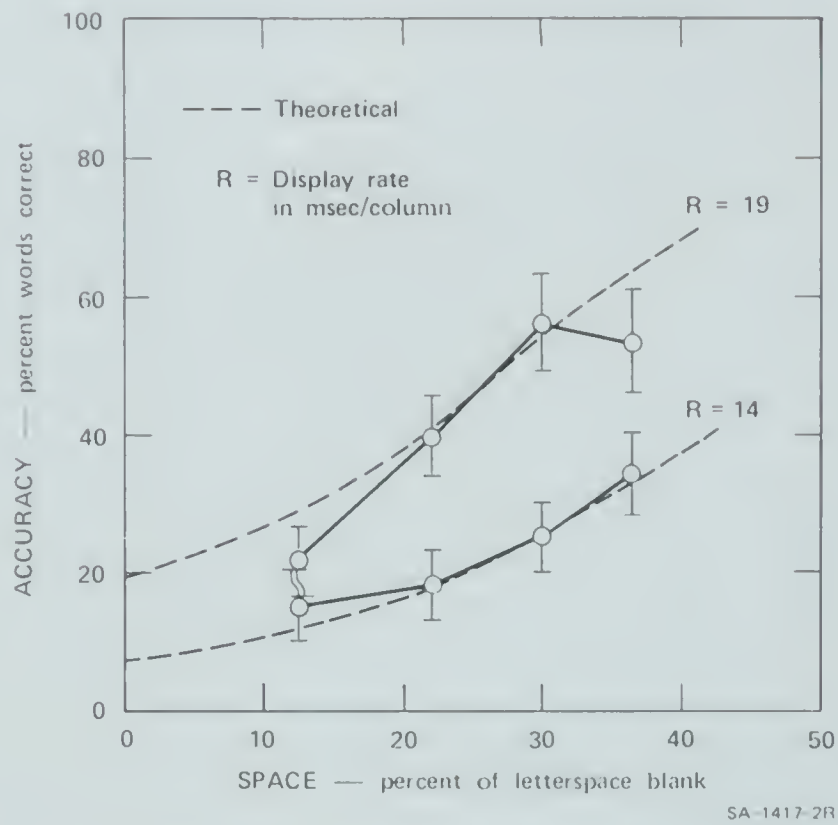

FIGURE 10. THE EFFECT OF INTERLETTER SPACING— BOTH MEASURED AND THEORETICAL FOR TWO DIFFERENT DISPLAY RATES.

What, then, does the model predict for the effect of window width changes on Optacon reading performance. Figure 11 shows the reading speeds that we would expect to measure if the Optacon window width could be varied from 0 to 7 ℓs. The constant-rate reading rate would increase linearly out to around 5 to 7 ℓs, where the limited short-term memory capacity (3, 9, 10), which acts like an internal window width restriction, would in turn limit the reading rate. Free-rate reading speeds, on the other hand, do not increase linearly. Free-rate reading is faster for small window widths due to ones ability to tailor his scanning speed to his processing requirements. At window widths above 2 ℓs, free-rate reading is slower due to the added tracking task. Since the Optacon is used for free-rate reading, we see that doubling the Optacon window width will not double the reading speed. However, it will increase the reading speed to a much more useful value.

It must be kept in mind that these results only apply to eventual performance levels, and long-term learning effects can become a problem in experiments designed to verify these predictions. As an example, about a year ago I ran an experiment designed to

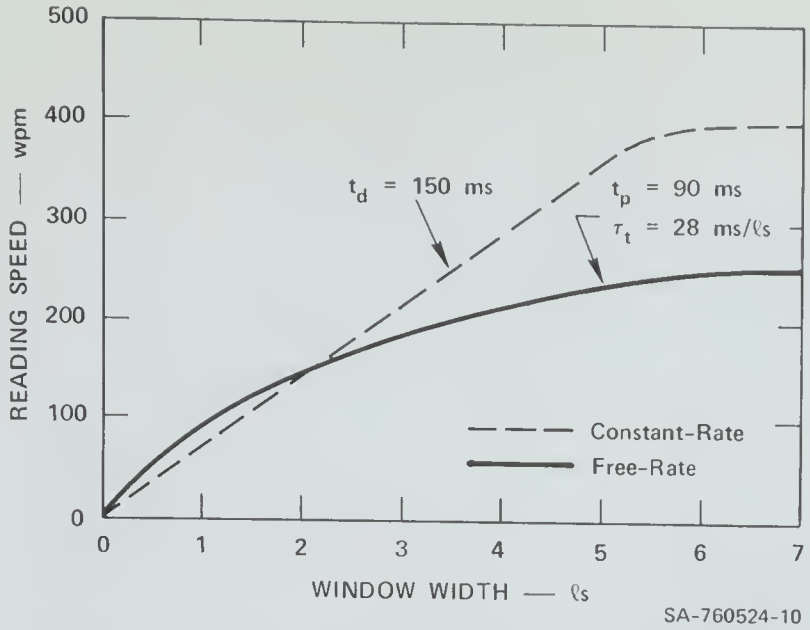

FIGURE 11. EXPECTED TACTILE READING SPEEDS FOR BOTH THE CONSTANT-RATE CASE AND THE FREE-RATE CASE.

test whether or not blind subjects proficient in Optacon reading could learn to read with a 1.5 ℓs tactile constant-rate display. We hoped that they would learn to utilize the additional information to produce an increase in their reading speed. Figure 12 shows the average results of that experiment. Their performance, as a function of window width, was periodically measured during 2 months of 1.5 ℓs training at 2-3 hours per week. The first and last performance curves are shown with the expected result which was calculated using the model and the subjects' individual Optacon reading performance curves. Notice that initially the extra information, contained in the wider display, confused them and their performance actually decreased with an increase in window width. However, after the training period, the wide-window display was just as good as the normal Optacon display but no better. Because of scheduling problems and school, the experiment had to be terminated. Thus we still do not know whether the subjects would have continued to learn so that their wide-window reading speed became faster than their normal-Optacon-display reading speed; or whether there is some, as yet, unknown limitation which prevents them from reading any faster. Hopefully, longer experiments will allow us to find the answer.

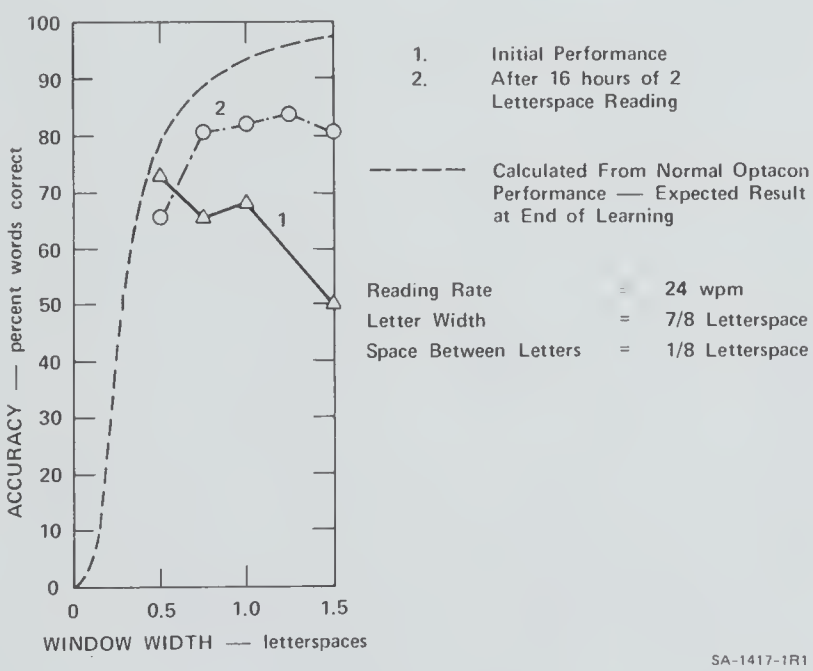

FIGURE 12. RESULTS FROM A SHORT TACTILE EXPERIMENT DESIGNED TO DETERMINE WHETHER A 1.5 ℓs WINDOW INCREASES THE READING SPEED AS PREDICTED. Average results from two adept blind Optacon users.

Conclusion

We now have a theory for reading textual material which can predict, at least some, reading data, but like all theories it must be proven. Because of the learning problem, it will take time and be difficult. I expect the way will be bumpy, but, at least, I have confidence that we are on the right road.

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